EPJ Web of Conferences **73**, 01003 (2014)
DOI: 10.1051/epjconf/20147301003

Overview of baryon resonances

Present status and perspectives

E.J. Downie[a]

The George Washington University, Institute of Nuclear Studies, 725 21st St. NW, Washington DC 20052, USA

Abstract. The quest to understand the physics of any system cannot be said to be complete as long as one cannot predict and fully understand its resonance spectrum. Despite this, due to the experimental challenge of the required double polarization measurements and the difficulty in achieving unambiguous, model-independent extraction and interpretation of the nucleon resonance spectrum of many broad and overlapping resonances, understanding of the structure and dynamics of the nucleon has suffered. The recent improvement in statistical quality and kinematic range of the data made available by such full-solid-angle systems as the CB and TAPS constellation at MAMI, coupled with the high flux polarized photon beam provided by the Glasgow Photon Tagger, and the excellent properties of the Mainz Frozen Spin Target, when paired with new developments in Partial Wave Analysis (PWA) methodology make this a very exciting and fruitful time in nucleon resonance studies. Here the recent influx of data and PWA developments are summarized, and the requirements for a complete, unambiguous PWA solution over the first and second resonance region are briefly reviewed.

1. Introduction

The nucleon resonance spectrum could be argued to be one of the most fundamental properties of the nucleon. If we cannot accurately predict the resonance spectrum of an object, then we do not truly understand its structure and dynamics. The quest to reach an understanding of the nucleon resonance spectrum has taken place over many decades and several continents, yet we still have not reached an absolute understanding. The study of the resonance spectrum is complicated by the fact that the resonances are broad and overlapping and to extract them from a measured spectrum, one must perform a Partial Wave Analysis. To date, the data we have measured are insufficient in number and not accurate enough to fully constrain Partial Wave Analyses, so there remain multiple solutions to the decomposition of the spectrum.

The A2 Collaboration at MAMI, in Mainz, Germany, is seeking to resolve this issue by performing a series of high-statistics, large-solid-angle, un-, single- and doubly polarized measurements of single

[a] On behalf of the A2 Collaboration. EJD is funded by NSF grant 1309130, e-mail: edownie@gwu.edu

and double meson photoproduction. They are also working in close collaboration with the theory group in Mainz to further develop partial wave analysis techniques and make targeted measurements, designed to specifically address several issues in existing data set and analyses. We describe herein the progress of these measurements and the state-of-the-art partial wave analyses, and look at the future outlook for baryon resonance studies in Mainz and in the wider field.

2. Energy independent partial wave analysis

The current state-of-the-art Partial Wave analysis in Mainz is done on the basis of energy-independent or single-energy fits, whereby the data are collected in approximately-10 MeV-wide photon energy bins. The angular distributions in each energy bin are fit independently. This requires very precise measurements over a very wide angular range, and the fits can then be represented as a series of points measured against an energy scale, rather than curves which assume some inherent energy dependence. This reduces model dependence dramatically. However, curent data is insufficient in statistics, kinematic range, and number of measured observables, to allow partial wave extraction by single energy fits at higher energies, such as in the region of the P11(1440) and the S11(1535), where one requires a set of five very well-measured observables. At lower energies, however, in the region just above the pion production threshold, the A2 collaboration have achieved the necessary accuracy to demonstrate the power of this new technique.

In order to perform such experiments with the required statistics and angular coverage, in both low and higher energy regions, one needs an appropriate detector system, with large angular coverage, high granularity and good energy resolution over a broad dynamic range, coupled with a high flux photon beam and a target capable of both longitudinal and transverse polarizations. Such systems can be found in MAMI, Bonn and at JLab. This report is focused on measurements made at MAMI.

3. Experimental setup

3.1 Photon beam

The MAMI accelerator produces an electron beam with a current of up to 100 μA. It has 100% duty cycle and electron polarization of up to 85%. It reaches a maximum energy of 1604 MeV with an energy spread of only 100 keV. The accelerator runs for 7000 hours per year, with each of the three A1, A2 and X1 collaborations taking beam consecutively. MAMI comprises an injection linac which provides injection for a series of three cascaded racetrack microtrons, followed by the world's only Harmonic Double Sided Microtron [1].

Upon entering the A2 experimental hall, the electron beam encounters a thin radiator. This radiator can be either amorphous, such as a thin copper foil or crystalline, usually a thin diamond radiator, for the production of linearly polarized photons. Circularly polarised photons are produced by using a polarised electron beam, with the highest polarisation transfer for the highest energy photons, those closest to the original beam energy. Most of the electrons pass through without interaction and are steered by the dipole magnet of the Glasgow Photon Tagger [2] into the Faraday cup, where the beam current is monitored. Those which give off photons in the Bremsstrahlung process are energy degraded and so are bent further by the dipole magnet to impinge on the focal plane detector system of the Glasgow Photon Tagger. The radiated photons have a continuous, $1/E$ spectrum. They travel down the experimental beam line unperturbed by the dipole field into the experimental area. The position at which the electron impinges on the focal plane is determined by its energy and the energy of the photon can then be deduced using simple energy conservation through $E_\gamma = E_0 - E'_e$. The reaction products are linked to the photon energy by timing coincidence. We thereby produce a quasi- monoenergetic photon beam.

3.2 Target

The photon beam enters the target which, depending on the experiment, can be a simple cryogenic liquid hydrogen or liquid deuterium target, contained in a Kapton cell, or, for polarized target measurements, the Mainz Frozen Spin Target (FST) (polarized butanol). The frozen spin target is a complicated device, requiring a horizontal dilution cryostat, capable of stably holding temperatures as low as 25 mK at mK-level stability for several weeks, a 2.45 Tesla superconducting polarizing magnet with very good homogeneity, a microwave polarization system and an NMR system in order to track and measure the polarization. The Mainz target is transversely polarized when a thin superconducting saddle coil is installed to provide the holding field during measurement, as during the first running period with polarized target; or longitudinally polarized when the thin superconducting solenoid replaces the saddle coil, as in the current polarized target measurement period. Due to the reasonably high holding field (ca. 0.35 T transverse, 0.5 T longitudinal), and the exceptionally low, stable temperatures achieved, the Mainz Frozen Spin Target has a relaxation time of the order of one to two thousand hours. This reduces the frequency with which one has to stop measuring in order to repolarize the target to approximately once per week of running. This allows for good systematic control of the experiment and maximizes the time spent in gathering useful data. Within the first period of polarized target running, the target proved itself exceptionally reliable, being cold for more than 4500 hours with only one minor blockage in the initial testing phase.

3.3 Crystal ball detector system

Reaction products exiting the target between 21° and 159° in the polar angle, θ, enter the Crystal Ball (CB) spectrometer. The CB provides position, energy and timing information for both charged and neutral particles over the full azimuthal range (with the exception of a slight gap between the hemispheres for structural support). It is a highly segmented 672-element NaI(Tl), self triggering photon spectrometer constructed at SLAC in the 1970's. Each element is a truncated triangular pyramid, 41 cm (15.7 radiation lengths) long. The CB has an energy resolution of $\Delta E/E = 0.020 \cdot E[GeV]^{0.36}$, angular resolutions of $\sigma_\theta = 2 \ldots 3^\circ$ and $\sigma_\phi = \sigma_\theta / \sin\theta$ for electromagnetic showers [3]. The readout electronics for the Crystal Ball were completely renewed in 2003, and it now is fully equipped with SADCs which allow for the full sampling of pulse-shape element by element. In normal operation, the on-board summing capacity of these ADCs is used to enable dynamic pedestal subtraction and the provision of pedestal, signal and tail values for each element event-by-event. Each CB element is also equipped with multi-hit CATCH TDCs. During recent data acquisition upgrades, an FPGA-based triggering system replaced the former hard-wired trigger, which allowed for energy-sum and rough multiplicity triggers based on OR's of 16 crystals. The FPGA triggering has vastly improved the sophistication and accuracy of the clustering algorithm and has added extra capabilities, such as the possibility to request co-planar or charged particles. The Crystal Ball has a marvelous dynamic range, as exhibited in the first article published by the new collaboration [4], were 4.4 MeV photons from the first excited state in carbon 12 were detected in the NaI in coincidence with the photons from pi^0 decay.

Between the target and the CB, the reaction products encounter the Particle Identification Dectector 2 (PID2), a barrel of 24 plastic scintillators. They then enter a pair of Multi Wire Proportional Chambers (MWPCs). The PID2 allows the determination of charged particle species using a $\Delta E/E$ methodology (see Fig. 3). This is primarily used for the separation of charged pions, electrons and protons. The PID2 covers from 15° to 159° in θ.

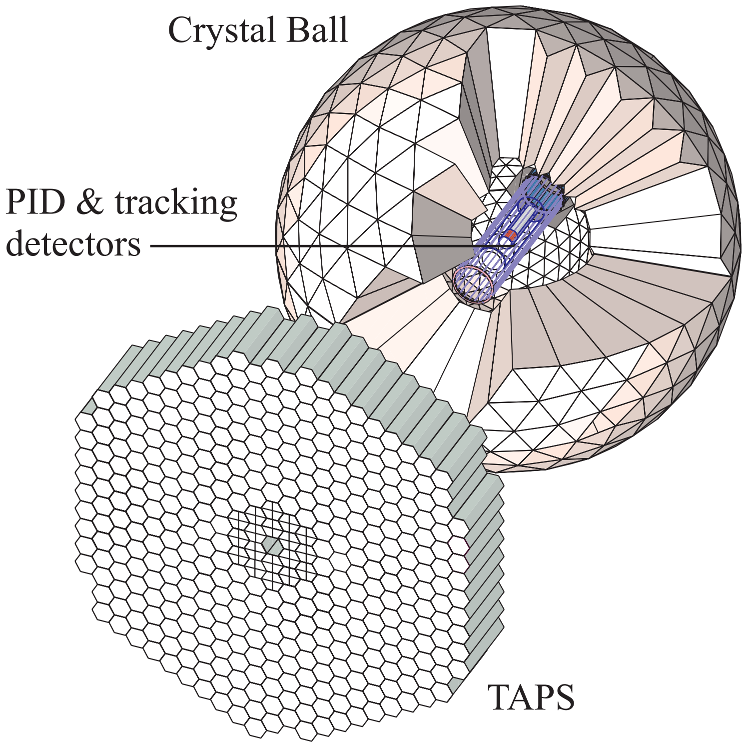

Figure 1. The A2 detector setup: The Crystal Ball calorimeter, with cut-away section showing the inner detectors, and the TAPS forward wall.

Photons entering the CB spread their energy deposit over several crystals. Reconstructing the locus of the photon via an energy-weighted sum of the crystal positions allows for location of the photon to better than the crystal pitch. As charged particles typically deposit energy in clusters of only one or two crystals, one can improve their tracking using the MWPCs. These MWPCs are similar to those installed inside the CB during the first round of MAMI-B runs [5]. The most significant difference is that all detector signals are taken at the upstream end of the MWPCs, minimizing the material required and facilitating particle detection in the forward polar region.

Within each chamber both the azimuthal and the longitudinal coordinates of the avalanche will be evaluated from the centroid of the charge distribution induced on the cathode strips. The location of the hit wires(s) will be used to resolve ambiguities which arise from the fact that each pair of inner and outer strip cross each other twice. The angular resolution (rms) is $\sim 2^\circ$ in the polar angle θ and $\sim 3^\circ$ in ϕ, the azimuthal angle.

The full, almost hermetic, detector system is shown schematically in Fig. 1 and the measured two-photon invariant mass spectrum is shown in Fig. 2.

3.4 TAPS forward wall

The TAPS forward wall is composed of 384 BaF_2 elements, each 25 cm in length (12 radiation lengths) and hexagonal in cross section, with a diameter of 59 mm. The front of every TAPS element is covered by a 5 mm thick plastic veto scintillator. The single counter time resolution is $\sigma_t = 0.2$ ns, the energy resolution can be described by $\Delta E/E = 0.018 + 0.008/E[GeV]^{0.5}$ [3]. The angular resolution in the

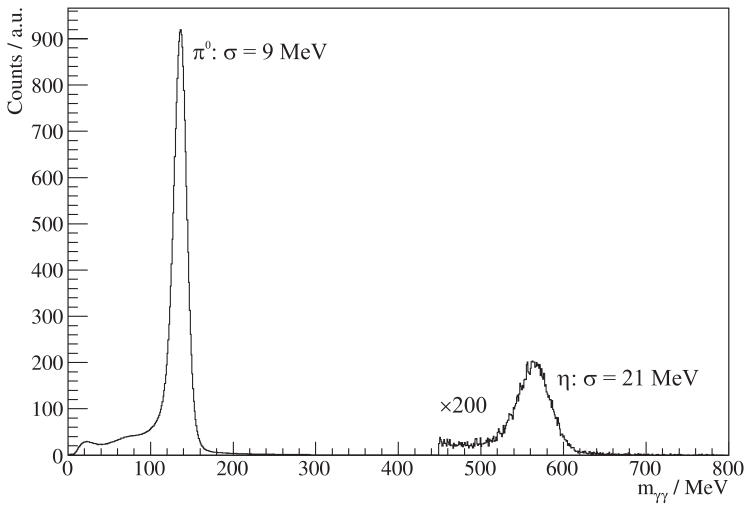

Figure 2. Two photon invariant mass spectrum for the CB/TAPS detector setup. Both η and π^0 mesons can be clearly seen.

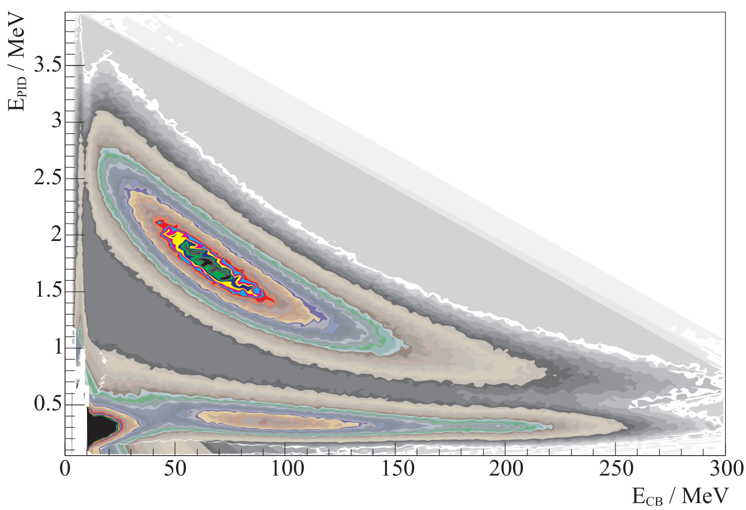

Figure 3. A typical $\Delta E/E$ plot from the Crystal Ball and the PID2 detector. The upper curved region is the proton locus, the lower region contains the pions and the peak towards the origin contains mostly electrons.

polar angle is better than 1°, and in the azimuthal angle it improves with increasing θ, being always better than $1/R$ radian, where R is the distance in centimeters from the central point of the TAPS wall surface to the point on the surface where the particle trajectory meets the detector. The TAPS readout was custom built for the beginning of the CB@MAMI program and is effected in such a way as to allow particle identification by Pulse Shape Analysis (PSA), Time Of Flight (TOF) and $\Delta E/E$ methods (using the energy deposit in the plastic scintillator to give ΔE). TAPS also contributes to the FPGA-effected trigger. The 2 inner rings of 18 BaF_2 elements have been replaced by 72 $PbWO_4$ crystals each 20 cm in length (22 radiation lengths). The higher granularity improves the rate capability as well as the angular resolution. The crystals are operated at room temperature. The energy resolution for photons is similar to BaF_2 under these conditions.

4. Building a partial wave analysis framework: The threshold region

In order to prototype a Partial Wave Analysis framework, one should begin in the threshold region as fewer partial waves need to be employed in order to describe the data. By using only S and P waves: the E_{o+}, P_1, P_2 and P_3 can be extracted using only a well-measured differential cross section and the linearly polarized photon beam asymmetry $\Sigma = (d\sigma^{\perp} - d\sigma^{\parallel})/(d\sigma^{\perp} + d\sigma^{\parallel})$. The P waves are real at this point as it is below the rage where the Δ starts to play a large role, and the imaginary part of the E_{0+} amplitude can be determined using unitarity. One extracts four real coefficients from the data, A, B, C and D, on the assumption that $(d\sigma/d\Omega) \sim (A + B \cdot \cos\theta + C \cdot \cos^2\theta)$ and that $(\Sigma \cdot (d\sigma/d\Omega)) \sim (D \cdot \sin^2\theta)$. The first direct experimental determination of multipoles in the threshold region can be found in [6], with both single-energy and the energy-dependent fits by Tiator and Kamalov.

The results of the single-energy fits can be compared to predictions based on a variety of theories and models. The region of validity of such models used to describe data can be nicely tested by plotting the reduced χ^2 of the various fits as a function of energy, as demonstrated by C. Fernadez Ramirez and A. M. Bernstein in [7]. In order to reduce model dependence even further, and determine the imaginary part of the E_{0+} amplitude without relying on unitarity, one would require an extra measurement: the transversely polarized target asymmetry, T. A first measurement of T has taken place at MAMI, and, at the time of writing, the results are under analysis. It is, however, extremely challenging to extract such threshold asymmetries from polarized target data.

5. Getting beyond the threshold region in π^0 photoproduction

In the region around the $P_{11}(1440)$ and the $S_{11}(1535)$, it is very clear that two observables are insufficient to completely determine the resonance content, however, it is postulated that five well-measured observables should be sufficient. In order to test this hypothesis, pseudo-data were generated for six observables: σ, Σ, T, F, E and G, using the Mainz-based MAID partial wave analysis as input. The pseudo-data were then analysed by the SAID partial wave analysis group at the George Washington University. The SAID analysis recovered the original input partial wave solution. This demonstrates the feasibility of such an extraction, which is recorded in detail in [8]. However, it should be noted that a rough scan of six observables is far from sufficient for such an analysis. The data must cover a large solid angle range and be of sufficient statistical quality as to remove ambiguities in the fit. The level of statistical accuracy represented in the pseudo-data corresponds to approximately six to eight years of measurement in A2, making the extraction of such detailed partial waves in the regions where we are currently least certain of the partial wave contributions, and where we have most interest to measure, a long-term project requiring substantial manpower and investment. There is no short-cut to an understanding of the nucleon resonance spectrum, but until the resonance spectrum can be accurately and uniquely reproduced and decomposed, which is not yet the case even at these relatively low energies, the nucleon cannot be said to be fully understood.

The work in the first and second resonance region has, however, begun, with independent analyses of the A2 measurements of the observables T and F in π^0 photoproduction underway. These massively increase the angle and energy coverage of the previous world data in T and provide world-first measurements in F.

The reason for multiple parallel analyses is that polarized targets are not pure hydrogen, but some other chemical, in the case of A2: butanol, frozen into small, spherical beads, immersed in a liquid helium bath. This is necessary in order to allow the target material to be polarized and remain sufficiently cold to hold the polarization for appreciable measurement periods. It does, however, pose problems in terms of background channels and impurities in the final event sample. There are multiple ways of analyzing the data to take account of these backgrounds. In the A2 collaboration, three methods are in common use: (1) one can simply calculate the asymmetry, complete with background, and then fit the data to determine a "dilution" factor; (2) one may combine demanding the nucleon in order to eliminate coherent backgrounds, from whole nuclei, with a carbon subtraction measurement, whereby one replaces the butanol with a carbon foam target of similar dimensions and a density calculated to match the number of nucleons other than polarized protons in the target to remove quasi-free backgrounds; (3) one measures an absolute count rate asymmetry, to which only the polarized nucleons contribute. Method (3) may appear to be very clearly the best option, but in order to calculate the final asymmetry, one has to use all of the absolute normalization factors which normally drop out in an asymmetry measurement and, due to the nature of the frozen spin target, determining the absolute target density to high precision is very difficult. As all three methods have very different systematic contributions, having independent physicists analyzing the data in each of the different ways and checking that the results converge provides a very good measure of the systematic uncertainty in the extraction methods.

6. Partial wave analyses in η photoproduction and double meson photoproduction

One can not only meaure π^0 photoproduction, as some resonances are better accessed in other meson photoproduction channels. For example, the $S_{11}(1535)$, which is the dominant resonance in η-photoproduction. As the $S_{11}(1535)$ is so dominant, one requires polarization observables in order to disentangle the other partial wave contributions.

The η-photoproduction cross section on the proton was measured with great statistical precision in [9]. The quality of the data was such that a dip in the cross section became apparent at forward angles, around $W = 1660$ MeV. There is, however, no evidence in the data for any narrow structure. This is in contrast to the $\gamma D \rightarrow \eta n(p)$ and $\gamma^3 He \rightarrow n(pp)$ channels in η production on the neutron where a narrow structure is seen at approximately 1675 MeV. There are many possible explanations for this structure, which has also been seen in measurements by Graal, Elsa and Tohku-LNS, such as a possible nucleon resonance, a threshold effect or final state interactions. In order to clarify the nature of the structure and its origin, spin observables are being measured in this region for η production on both protons and neutrons.

At MAMI, approximately one thousand hours of transversely polarized data have been collected on transversely polarized deuterated butanol in order to produce asymmetries and analyze this structure in η production on the neutron. There already exist preliminary results for the transversely polarized data taken in this region on regular butanol, to access the proton asymmeties. These data yield both a large improvement in the world data set for the T and the worlds first measurement of the F asymmetry in this channel. As the prior world data were so statistically poor and kinematically sparse,and therefore the partial wave analyses in these channels disagree very strongly, this high quality data will have a large influence on improving PWA in this channel. These efforts will combine to provide a clearer understanding of the observed narrow structure. There have also been nuclear Compton Scattering measurements at MAMI in this region in order to try to clarify the situation. The publication of the proton η data, is at the time of writing, in progress.

In parallel to the wealth of new, high quality data being taken on single meson (π^0, η) photoproduction, double meson photproduction data is being accumulated. In the $\pi^0\pi^0$ and $\pi^0\eta$ channels, one has the potential to access some states below 2.5 GeV which are believed to couple strongly to final states with two pseudoscalar mesons. For example, in double pion production, the contribution of the $D_{13}(1520)$ is very strong above 650 MeV, but, below that point, models do not agree and do not describe the data well. Early analysis of dat indicates a strong $J = 3/2$ contribution and polarization observables should help to clarify its origin. The $\pi^0\eta$ channel has its own issues which will be covered by V. Kashevarov within this volume.

7. Conclusions and outlook

The aim of the baryon resonance program at MAMI is to measure six observables with the requisite systematic and statistical accuracy to allow a fully constrained partial wave analysis in the single energy fit formalism. The current partial wave analyses do not all agree and this hard-won improvement in data quality is anticipated to be especially valuable and necessary in the region of the $P_{11}(1440)$ and $S_{11}(1535)$, where current PWAs can describe the data equally well with very different partial wave content. Without this increase in data statistical quantity, kinematic coverage and the addition of further polarization observables, unique solution of the resonance content is not possible and one forfeits complete understanding of the nucleon resonance spectrum in photoproduction.

Recent progress in the threshold region of π^0 photoproduction prototype the single-energy-fit PWA methodology and clearly demonstrate its power. Pseudodata studies have shown both the full potential for a unique solution and the scale of the data-taking effort and care required in order to achieve this important aim. Recent data taken at MAMI and the preliminary analyses show promise and represent substantial steps in the right direction, but many years of extra effort are needed. Once one has covered π^0 and η production, double meson photoproduction channels will open other possible areas of investigation.

Finally, once a unique solution is reached in photoproduction channels, it will be necessary to compare the resonance spectrum/partial wave content established in photoproduction with that extracted from other methods, such as results from the BES and PANDA experiments. Once one observes a unique solution that agrees over multiple resonance production methodologies, it is safe to conclude that the extracted quantities truly are a property of the nucleon and not simply a function of the production mechanism.

References

[1] K. Kaiser, K. Aulenbacher, O. Chubarov, M. Dehn, H. Euteneuer et al., Nucl. Instrum. Meth. A **593**, 159 (2008)
[2] J. McGeorge, J. Kellie, J. Annand, J. Ahrens, I. Anthony et al., Eur. Phys. J. A **37**, 129 (2008), arXiv: [nucl-ex]0711.3443
[3] S. Prakhov et al., Phys. Rev. C **79**, 035204 (2009), arXiv:[hep-ex]0812.1999
[4] C. Tarbert et al., Phys. Rev. Lett. **100**, 132301 (2008), arXiv:[nucl-ex]0711.1839
[5] G. Audit, A. Bloch, N. D'Hose, V. Isbert, J. Martin et al., Nucl. Instrum. Meth. A **301**, 473 (1991)
[6] D. Hornidge et al., Phys. Rev. Lett. **111**, 062004 (2013), arXiv:[nucl-ex]1211.5495
[7] C. Fernandez-Ramirez, A. Bernstein, Phys. Lett. B **724**, 253 (2013), arXiv:[nucl-th] 1212.3237
[8] R. Workman, M. Paris, W. Briscoe, L. Tiator, S. Schumann et al., Eur. Phys. J. A **47**, 143 (2011), arXiv:[nucl-th]1102.4897
[9] E. McNicoll et al., Phys. Rev. C **82**, 035208 (2010), arXiv:[nucl-ex]1007.0777