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ELEMENTARY PARTICLES AND FIELDS
Experiment

Resolution of SPD Detector in the Search for Dibaryons with Small Energy Excitations

V. Andreev[1], A. Ivanov[2], B. Kostenko[2], V. Kurbatov[2]*, and Z. Kurmanaliev[3]

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Abstract—The existence of dibaryons, the systems with baryon number two, is one of the central questions in modern nuclear physics. It is closely connected with the problem of phase transitions in nuclear matter, various manifestations of which are being searched for in the experiments with colliding heavy nuclei. Since the theory of these processes is very difficult, the interpretation of such data usually contains large uncertainties. At the same time there is a possibility of understanding some features of these processes in the collision of the lightest nuclei—deuterons. Exploring such an opportunity at the future NICA SPD is the focus of this paper. It is shown that while using Kinematical fit technique at the simulation of the process $d + d \to d + X$ below meson production threshold, the accuracy of the estimation of the X mass is on the level 2—3 MeV/c when the deuteron moment of the NICA Collider is equal to 2.6 GeV/c (below MX is used as a mass of X, i.e. $MX = M_d + E_{\text{exc}}$, where M_d, E_{exc} are deuteron mass and excitation energy). The system X is called sometimes as dibaryons below.

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1. INTRODUCTION

One of the interesting opportunities offered by the future NICA SPD facility is to search for dibaryons in a two-nucleon system below the meson production threshold. There is still some probability of detecting them in direct collisions of neutrons with protons by peaks in the elastic n–p scattering cross section. Indeed, according to the data currently recommended by the Particle Data Group for their reliability and accuracy [1], in the region of momenta of colliding neutrons larger than 0.3 GeV/c, there are certain gaps in these cross sections that may contain such peaks. However, the idea of searching for six-quark states directly in the deuterium nucleus, first proposed in [2], is more important from the theoretical point of view. Indeed, their detection could serve as a key to explaining the EMC effect on the basis of a similar admixture of $6q$ states in quasi-deuterons of nuclei, the existence of which has long been proved by numerous experimental data [3]. One of the possible experimental manifestations of the prediction [2] may be the detection of peaks in the effective mass distributions of neutrons and protons that could be produced in reactions of direct knocking-out of the six-quark system from the deuterium nucleus in the reaction $d + (6q) \to d + n + p$. This paper presents the results of mathematical modeling of the processes of detecting such states at the NICA SPD facility in order to evaluate the requirements on the accuracy of measurements necessary for their observation.

The structure of SPD is shown in SPD TDR [4]. It looks more or less similar to the famous ATLAS and CMS Detectors at LHC. The conditions of the model study:

- The accelerator produces head-on dd collisions; the momenum of the colliding deuteron is 2.6 GeV/c, equivalent to 8.9 GeV/c on the fixed target as was in the experiment [5].
- SPD magnetic field is homogeneous and equal to $1T$.
- The transferred momentum of the unbroken deuteron is $t = -0.5$ (GeV/c)^2.
- It is assumed that X decays into $p + n$ isotropically in its rest system.
- E_{exc} is taken as a fracton of the π^0 mass equal to 1/4, 1/2, 3/4 (1.90935, 1.94310, 1.97685 GeV/c, respectively).

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[1] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia.

[2] Joint Institute for Nuclear Reaearch, Dubna, Russia.

[3] L.N. Gumilyov Eurasian National University, Astana, Kazakhstan.

[*] E-mail: `kurbatov@jinr.ru`

- All the collisions take place at the central point of the detector (coordinates $x = y = z = 0$), the deuteron and the proton tracks and the primary vertex are reconstructed and the dibaryon has zero decay width.

Another thing worth mentioning is that by the resolution is meant the width of the distribution (or a signal) of mass estimates of X. In electronics the width of any signal is characterized by the so-called FWHM (Full Width at Half Maximum) and if the signal is purely Gaussian the sigma of this Gaussian satisfies the equation $1.18\sigma = 1/2\mathrm{FWHM}$. So the resolution here is specified as a σ of the Gaussian function approximating the peak region of the MX distribution.

2. SIMULATION AND PROCESSING EVENT SAMPLES

The simulation and reconstruction of events were done with the SpdRoot package [6]. After the reconstruction of an event,we have the following observables:

- Three-momenta of the deuteron and the proton.
- Lengths and the difference between times of flight (TOFs) of the deuteron and the proton.

Three-momenta of charged particles are reconstructed using GenFit2 code built into SpdRoot, which in addition to the estimates, gives their error matrices (covariancies). As for TOFs, given that we know the absolute values of the deuteron and the proton momenta and their flight lengths, we can calculate the difference in their times of flight (here the problems of particle identification are not discussed).

So we should find the best estimates of the deuteron and the proton three-momenta—six parameters, having seven observables (estimates of three-momenta of the deuteron and the proton and the difference in their TOFs).

Certainly, the estimation should be done according to Maximum Likelihood Method [7] and total likelihood function is the production of three likelihood functions

$$L_{\text{tot}} = L_{(\mathrm{TOF}d - \mathrm{TOF}p)} L_{\mathbf{p}_d} L_{\mathbf{p}_p}. \tag{1}$$

Here, $L_{(\mathrm{TOF}d - \mathrm{TOF}p)}$ is the likelihood function for the difference of the deuteron and the proton TOFs and we should say a few words about it. SPD is supposed to run in a triggerless mode, so we do not have event production time. On the other hand TOF system of SPD measures the time of proton and deuteron hits and we have the difference $\mathrm{TOF}^m_{\text{dif}} = \mathrm{TOF}_d - \mathrm{TOF}_p$ and can use it at the parameter estimation. TOF_d and TOF_p are the functions of the deuteron and proton velocities(or their momenta). We may write the following:

$$L_{(\mathrm{TOF}d - \mathrm{TOF}p)} \approx \exp\left(-1/2(((\mathrm{TOF}_d - \mathrm{TOF}_p) - \mathrm{TOF}^m_{\text{dif}})/\sigma_{\text{dif}})^2\right). \tag{2}$$

Here $\sigma_{\text{dif}} = \sqrt{2}\sigma_{\text{tof}}$, where σ_{tof} is the error of TOF measurement equal to 60 ps.

As for $L_{\mathbf{p}_d}$ and $L_{\mathbf{p}_p}$ they arise from the measurements from TD (Track Detector system consisting of Vertex Detector and Drift Tubes). So for $L_{\mathbf{p}_d}$ we have

$$L_{\mathbf{p}_d} \approx \exp\left(-1/2(\mathbf{p}^t_d - \mathbf{p}^m_d)\mathrm{Cov}^{-1}_d(\mathbf{p}^t_d - \mathbf{p}^m_d)^T\right). \tag{3}$$

Here $\mathbf{p}^t_d$ and $\mathbf{p}^m_d$ are three-vectors of the deuteron momentum ($\mathbf{p}^t_d$ stand for the parameters to be found by model fit) and their estimates $\mathbf{p}^m_d$ found by GenFit2 during the reconstruction. Cov^{-1}_d is the inverse of the Covariance matrix for the deuteron also found by GenFit2.

Analogously, for the proton

$$L_{\mathbf{p}_p} \approx \exp\left(-1/2(\mathbf{p}^t_p - \mathbf{p}^m_p)\mathrm{Cov}^{-1}_p(\mathbf{p}^t_p - \mathbf{p}^m_p)^T\right). \tag{4}$$

Here, $\mathbf{p}^t_p, \mathbf{p}^m_p, \mathrm{Cov}^{-1}_p$ have the same meaning explained above but for the proton.

So, the number of observables is seven, the number of parameters to be found, i.e., deuteron and proton three-momenta is six.

Then during minimization we should require the fulfilment of the following equation:

$$M^2_n = (M^4_R - P^4_d - P^4_p)M2(), \tag{5}$$

where M_n, M^4_R, P^4_d, P^4_p are the neutron mass, the sum of the colliding *dd* four-momenta, and the four-vectors of the deuteron and the proton in a final state respectively. In other words, we should estimate parameters using so-called constraint fitting technique.

3. FIT

Fitting was done by the Fumili code developed and realized in FORTRAN in the early 1960s by S. Sokolov and I. Silin [8]. Later it was rewritten in C [9] and used extensively in many applications and also here. There are three methods of constrained minimization known to the authors [10–12]. In the current work we used the method [11].

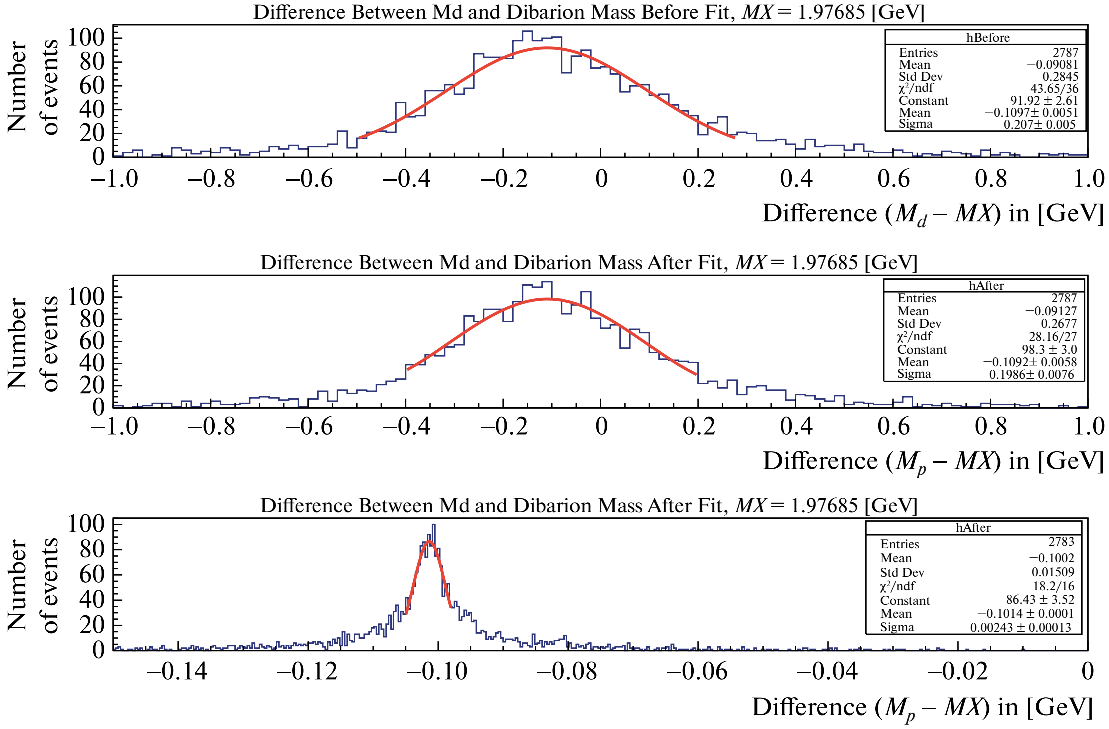

Fig. 1. Distributions of differences $M_d - MX$ (M_d, MX are the deuteron and reconstructed dibaryon massess) when the dibaryon excitation energy $3/4m_{\pi^0}$. From top to bottom: Option 1, Option 2, Option 3. The solid curve is a fit by Gaussian, a range of fit was selected by eye. All the values are in GeV/c.

Table 1. The results of fitting ($M_d - MX$) in all the Options in the form the mean $\pm\sigma$ for all MXs; RMS is shown in parentheses; everything in GeV/c

$M_d - MX$	Option1(RMS)	Option2(RMS)	Option3(RMS)
−0.0338	−0.05874 ± 0.2181 (0.2913)	−0.0545 ± 0.2117 (0.2874)	−0.0339 ± 0.0020 (0.0083)
−0.0675	−0.0929 ± 0.2213 (0.2911)	−0.0753 ± 0.2043 (0.2794)	−0.0676 ± 0.0027 (0.0126)
−0.1013	−0.1097 ± 0.2070 (0.2845)	−0.1092 ± 0.1986 (0.2677)	−0.1014 ± 0.0024 (0.0151)

4. METHODS FOR THE DIBARYON MASS ESTIMATIONS

$$MX = (M_R^4 - P_d^4)M(). \tag{6}$$

The mass of X-system can be found by the analysis of missing mass spectrum, when the mass is calculated by the formula (6), where M_R^4 is the sum of the colliding *dd* four-momenta, P_d^4 is the estimate of the reconstructed four-momentum of the deuteron. The estimate can be taken as either the value obtained by fitting only deuteron hits in TD system (Option 1), or the value from fitting all the information (deuteron hits, proton hits and TOF difference between deuteron and proton; this is an Option 2). As was said above during the reconstructon of the deuteron momentum exploiting all the registered information (as in Option 2) we can do constrained fit i.e. taking into account (5). The latter is called as an Option 3.

Comparing the results of Option 3 with Option 2 (it is necessary to compare σ values) we see amazing improvement in the resolution MX. The length of this article is not enough to show the result of fits for all MXs in the form of figures, so we show only one—the results of fitting for $MX = 3/4m_{\pi^0}$, Fig. 1.

In Table 1 we show the results of fitting in all the Options and the RMS value of the distributions for all dibaryon MXs analyzed here.

5. CONCLUDING REMARK

Hypothetical production of dibaryons with the mass in the range $M_d < MX < M_d + m_{\pi^0}$ is simulated in the reaction $d + d \to d + X$, where X means a dibaryon decaying into the proton and the neutron with the transfer momentum deuteron of $-0.5\,(\mathrm{GeV}/c)^2$ and studied under simplified assumptions. The decisive improvement in the parameter estimation in the analysis was obtained with using the kinematical fit technique, giving improvement by a factor $\approx 75 - 100$ with the resolution in dibaryon mass $\approx 2 - 3$ MeV$/c$. The resolution of the Detector at the level of few MeV$/c$ certainly opens the way to answer the question about the existence of dibaryons with small energy excitation.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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