PRODUCTION OF MESONIC STATES AT COSY–JÜLICH AND AT LEAR*

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COSY–Jülich at the Forschungszentrum Jülich–KFA and LEAR at CERN are proton and antiproton cooler rings, respectively, with similar, supplementary, and opposite features at the same time for studying hadronic strong interaction properties. In this written contribution from the two internal target experiments COSY-11 (which is in preparation and will be installed early 1994) and JETSET (which is in a data taking status at CERN) only an outline of the experiment at COSY–Jl̈ich will be given. The interesting results of the JETSET experiment, where the $\bar{p}p \rightarrow \phi\phi$ reaction has been studied at different incident p̄p momenta, are still in a preliminary status and have been presented elsewhere, recently (O. Steinkamp at the HADRON'93 conference and K. Röhrich at the PANIC'93 conference, see the respective proceedings). The main physics case for both experiments is the production of mesons and mesonic states involving strangeness.

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1. Introduction

In the Standard Model of particle physics the major difficulty arises due to the self coupling of the gluon force field resulting in the fast running coupling constant. At high four-momentum transfer this coupling constant leads to the asymptotic freedom, whereas at low momenta QCD predicts a strong increase of the coupling constant resulting in infrared slavery. Thus, confinement prevents an unburdened insight into that part of physics which is of special interest, since nature is made out of hadrons which are subject to forces with ranges in the order of hadronic dimensions.

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Beyond the naive quark model, QCD theory expects that other quark-gluon combinations should exist as hybrids, glueballs and $q\bar{q}$ $q\bar{q}$ states. Thus mesonic objects with quantum numbers as $J^{PC} = 0^{--}$ or 1^{-+} or charge $Q = 2$ would indicate exotic hadronic structures. However, in the search for such exotic hadrons it should be realized that the simple meson spectroscopy as evaluated in the u-, d-, and s-quark antiquark triplet of flavour SU(3) can tell us much about the nature of quark confinement.

The pseudo-scalar meson and the vector meson nonet are experimentally confirmed and in textbooks interpreted as members of $q\bar{q}$ multiplets. Indications arose that this conventional interpretation might be too simple; employing an effective quark model description Krewald *et al.* [2] recently pointed out that the neutral ρ meson for instance is dominated by a $\pi^+\pi^-$ final state interaction and that the ϕ meson might have as little as only 50% $s\bar{s}$ content. In addition, the quark or even gluon contents of the η and η' mesons are still under discussion.

The p-wave multiplets are even less understood. The $f_0(975)$ and $a_0(980)$ mesons are controversially discussed as either being $q\bar{q}$ scalar mesons or being two-quark–two-antiquark states or even being of $K\bar{K}$ molecule structure. It is essential that more work is needed to confirm the picture of mesons and mesonic states and their type of interactions.

COSY–Jülich with protons of momenta up to $\simeq 3.3$ GeV/c and with high precision due to phase space cooling is predestined for such kind of studies. In proton-proton interactions a total energy of $\sqrt{S} = 2.86$ GeV is achieved but due to baryon number conservation only single mesons or few meson combinations with masses up to the ϕ meson (1.02 GeV/c^2) can be observed *via* their production, reaction dynamics and decay.

LEAR at CERN on the other hand is a baryon number $B = 0$ facility as long antiprotons interact with protons and thus at the highest momentum of 2 GeV/c a total energy of $\sqrt{S} = 2.43$ GeV is available for the formation of new states of hadronic matter.

A further attractive feature of high precision cooler ring beams is the threshold production reaction, where the full center of mass phase space is pushed into a small laboratory angle cone. This allows a limited forward detection of ejectiles for a complete exclusive measurement. In addition, threshold studies are limited to only a few partial waves which might result in an easier interpretation; though, in general, threshold cross sections are rather small.

Free of contamination windowless internal targets (atomic beam or cluster targets) as thin as $\simeq 10^{14}$ atoms/cm^2 can be used in cooler rings, still providing high luminosities up to a few 10^{31} cm^{-2}s^{-1}. This advantageous feature of low target density and high luminosity results in the possibility of studying both atomic electromagnetic and nuclear strong interaction physics (it is known that long range Coulomb interaction can give valuable information about the strong interaction with its much shorter range). Experiments without the danger of secondary reactions in the target are possible under these circumstances.

The disadvantage of the beam pipe in an internal target experiment, where no reaction ejectiles can be registered at low angles, might be diminished by using a magnetic dipole system as suggested by the COSY–11 experiment.

2. Motivation for experiments at small angles

Based on the concept of Yukawa the baryon-baryon interaction can be described by exchange of mesons. The long range part of the interaction is determined by the π exchange whereas mesons with heavier masses contribute significantly to the interaction at shorter distances. At sufficient total energies $\sqrt{s}$ the otherwise virtual exchange-mesons can be produced as real particles on the mass shell. They might propagate between the baryons and/or they can leave the interaction zone consuming the available center of mass (excitation) energy and be observed in an appropriate detector system. Reactions like $pp \to pp\pi^0$ or $pp \to pn\pi^+$ or $pn \to pp\pi^-$ have attracted considerable interest for such investigations [3, 4, 5] at the new cooler accelerators. Presently, a widely unknown research field of questions opens here, as for instance the determination of the meson–nucleon coupling constants $f^2(i)$, which both experimentally and theoretically seems to be rather well known for the π meson [6] but insufficiently known for other mesons.

Furthermore, the heavier mesons determine particularly the short range forces of the strong interaction, a regime where the dualism of one-meson exchange on the one side and quark–gluon descriptions on the other side is still in discussion. Sufficient high beam energies or beam momenta are needed in order to cross the particular meson production thresholds, see Table I.

In the COSY–11 experiment we want to restrict ourselves to the study of the threshold behaviour of the *(i)* "few π mesons", *(ii)* heavier mesons at about 1 GeV/c^2, and *(iii)* mesonic state — hadronic and possibly electromagnetic production, states or resonances with very small widths. Especially two-meson objects are of particular interest, since they are the simplest systems involving the interaction between hadrons. These two-meson $q\bar{q} - q\bar{q}$ combinations open just one additional degree of quark structure complication over the single $q\bar{q}$ meson or qqq baryon.

TABLE I

Masses and threshold parameters for particle production in pp interactions

Meson(s)	Mass	Threshold	
		P_{beam}	E_{beam}
	(GeV/c^2)	(GeV/c)	(GeV)
π^0	0.135	0.777	0.280
$\pi^\pm$	0.140	0.792	0.290
$\pi^+\pi^-$	0.279	1.219	0.600
$\pi^+\pi^-\pi^0$	0.419	1.617	0.931
η	0.549	1.986	1.258
$\pi^+\pi^-\pi^+\pi^-$	0.558	2.012	1.283
$\eta\pi$	0.688	2.390	1.629
$\pi^+\pi^-\pi^+\pi^-\pi^0$	0.698	2.418	1.655
ρ	0.770	2.632	1.856
ω	0.783	2.670	1.892
$\eta\pi\pi$	0.828	2.807	2.021
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	0.837	2.836	2.048
$\rho\pi$	0.905	3.043	2.246
$\omega\pi$	0.918	3.083	2.285
η'	0.958	3.208	2.404
f_0	0.975	3.263	2.457
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$	0.977	3.269	2.463
a_0	0.983	3.288	2.481
K^+K^-	0.987	3.302	2.494
K^0K^0	0.995	3.327	2.519
ϕ	1.020	3.404	2.593

3. Meson production via the proton-proton interaction

In the excitation function of hadronic collisions the reaction mechanism is intimately connected to the coupling of nuclear degrees of freedom. With increasing momentum heavier mesons became more and more important as exchange particles mediating the short range part of the strong interaction force. The interpretation of experimental data from IUCF [3] on the basic pion production reaction pp $\rightarrow$ ppπ^0 is directly related to the pion-nucleon dynamics. Calculations of the pp $\rightarrow$ ppπ^0 total cross section at threshold with the final nucleons in a relative S-state including pion rescattering in the πN S-wave and in the P-wave through the $\Delta(1232)$ resonance in addition to the direct production underestimate the experimental results by a factor of three to four [7]. Similar problems arise from the precise data of pp $\rightarrow$ nπ^+ measurements [4], however, we learned during this conference from H.O. Meyer [8] that this factor seems to be understood.

The large cross section for the η production in the pd $\to {}^3$He η reaction observed at SATURNE [9] governed different reaction mechanism speculations. Considerably stronger than in the case of π-production the elementary η production process near threshold is expected to be dominated by the N*(1535) S_{11} resonance whereas the nonresonant contribution to the η-production is regarded as being negligible on the basis of the weak NNη coupling constant. Additional experiments on investigations of this reaction are presently being performed [10] or in preparation [11, 12].

Is the meson production a cooperative process where the available energy is at least partly (at threshold totally) converted into the meson mass? In the nuclear collision such cooperative effects might be due to both nucleon correlations and quark dynamical effects in coherent productions *via* gluonic intermediate states. In the nucleon collision "only" the quarks of the two nucleons act in producing a new meson. In this framework investigations of production strength and production dynamics of heavier mesons are of special interest, since they probe the elementary q$\bar{\text{q}}$ production including different flavours.

Though the set-up of the COSY–11 experiment is certainly optimum for meson production close to threshold, the interesting field of meson decay studies should at least be mentioned here as a further experimental extension at COSY–Jülich. Isgur [13] pointed out that within the constituent quark model the transition rate between ground state of vector meson and pseudoscalar meson nonets as

$$\rho \to \pi\gamma \text{ or } \to \eta\gamma, \qquad \omega \to \pi\gamma \text{ or } \to \eta\gamma, \qquad \phi \to \pi\gamma \text{ or } \to \eta\gamma \text{ or } \to \eta\gamma$$

should be firmly predictable in QCD theory on lattice calculations. Relevant investigations of these transitions are regarded to be especially important since the transition amplitudes determine the relative meson quark contents. Nefkens [14] gives a strong pledge on the opportunities being available for probing the Standard Model of particle physics and testing chiral perturbation theory of low energy QCD by measuring decay modes of light mesons with high precision.

4. Mesonic states

The repulsive core of the nucleon-nucleon system complicates the exploration of its full six quark structure due to quark exchange effects [15]. Thus, an understanding of rather simple two-quark–two-antiquark object as the simplest nonnatural hadronic system would be a challenge in low energy hadron physics. In addition, the qq$\bar{\text{q}}\bar{\text{q}}$ system is a more readily accessible variety since *e.g.*, the $\pi^+\pi^+$ and $\pi_+\pi^-$ combinations have very different quark exchange characteristics [13].

Reaction mechanisms for double pion production are displayed in Fig. 1, and can either involve two Δ isobars, or an N^* having reasonably large probability for $N\pi\pi$ decay fractions like the $P_{11}(1440\ \text{MeV})$ resonance (30–50%).

Fig. 1. Reaction mechanisms for double pion production

In case the $\pi\pi$ interaction is considered to be of largest interest, those kinematical situations should be selected, where the relative pion momenta are minimal. In addition, the low energy $\pi\pi$ interaction seems to have some strong attractive but nonresonant components, since enhancements of low invariant $\pi\pi$ mass pairs have been reported in various experiments, including the "ABC"-effect [16] and meson decays as $\eta' \to \eta\pi^+\pi^-$.

5. Mesons in the range of 1 GeV/c^2

The mesons η', f_0, a_0 and ϕ are of special interest, since their structure of valence quarks involves strange quarks, and since they decay strongly into two mesons:

$\eta' \to \pi^+\pi^-\eta$ (44.1%) $\quad$ $f_0 \to \pi\pi$ (78.1%), $K\bar{K}$ (21.9%)
$a_0 \to \eta\pi$ (seen), $K\bar{K}$ (seen) $\quad$ $\phi \to K^+K^-$ (49.1%), $K^0_L K^0_S$ (34.4%), $\rho\pi$ (12.9%)

Thus the production dynamics of these mesons is of fundamental nature. Especially, investigations of the meson production at the reaction threshold appears to be appropriate in view of the sea-quark structure and its dynamical contribution to the nucleon.

Interpretations suggest that the f_0 meson (former notation $S*$) is in reality two close and narrow states where one of them contains $s\bar{s}$-quarks, the other should be a flavour singlet which couples to $\pi\pi$ and $K\bar{K}$ with similar strength. The discussion on possible gluonium candidates is still alive. Thus, some of these mesons — supposed to have widths in the order of 30 MeV/c^2 — could well exhibit an overlay of structures with much smaller widths. Another feature of these resonances is their decay into the $K\bar{K}$ channel if $\sqrt{s}$ is larger than the equivalent center of the resonance. This fact could suggest a hadronic $K\bar{K}$ nature of the resonances which in particular couples to an atomic structure as a kaonium.

6. A qq$\bar{q}\bar{q}$ interpretation

The scalar mesons f_0 and a_0 are difficult to be accommodated as $^3P_0 q\bar{q}$ states. Already in 1977 Jaffe [17] deduced from colour hyperfine interactions a low-lying "cryptoexotic" nonet of $qq\bar{q}\bar{q}$ states in the bag model and suggested to identify f_0 and a_0 as members of that nonet.

The main argument in favour of the a_0 as a $qq\bar{q}\bar{q}$ state interpretation is its almost complete degeneracy in mass with the isoscalar $f_0(975)$, together with the observation that the $f_0(975)$ couples much more to the $\mathrm{K}-\bar{\mathrm{K}}$ than to the $\pi - \pi$.

7. Arguments in favour of q$\bar{q}$ and gluonic nature

Close [18] summarized the discussion of the literature in this mass range that "two pieces of circumstantial evidence for a gluonic component have recently emerged. The process $\Psi \to \phi\pi^+\pi^-$ is doubly forbidden by the OZI rule (see Fig. 2 left) and thereby offers a good glueball signal: $\Psi \to \phi G$; $G \to \pi^+\pi^-$. The $S*(975)$ is a sharp and clear bump in the $\pi^+\pi^-$ invariant mass spectrum.

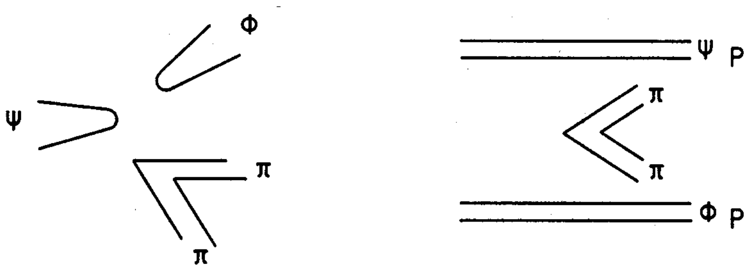

Fig. 2. OZI forbidden diagram of the process: $\Psi \to \phi\pi^+\pi^-$ (left) and the suggested diagrams: hypothetical $\Psi\phi \to \Psi\phi + \pi\pi$, realistic $\mathrm{pp} \to \mathrm{pp} + \pi\pi$ (right).

Twisting the diagram of Fig. 2 (left) for $\Psi \to \phi\pi^+\pi^-$ around one would expect similar structures to show up in the hypothetical $\Psi\phi \to \Psi\phi + \pi\pi$ diagram or the realistic central region in $\mathrm{pp} \to \mathrm{pp} + \pi\pi$ (Fig. 2 right). Data on this reaction have been taken [19] and analyzed by Au *et al.* [20]. There is clear indication of the S^* presence as a shoulder in the data. The data quality is such that Au *et al.* [20] resolve two signals in the $S*$ region; $S(988)$ contains $s\bar{s}$ quarks whereas $S(993)$ is a flavour singlet (coupling to $\pi\pi$ and $\mathrm{K\bar{K}}$ with similar strengths) and a possible gluonium "candidate'. In an early analysis three resonance poles were claimed in the 1 GeV/c^2 mass region resulting from a K-matrix coupled $\pi\pi$ and $\mathrm{K\bar{K}}$ channel formalism

[21]. A more recent similar analysis [22] using ISR data on central π production [23] as well as DM2 and MARKII results on $J/\Psi(1S) \to \phi K\bar{K}$ and photoproduction data on $D_s \to \pi\pi\pi$ disfavors a $K\bar{K}$ molecule interpretation of the $f_0(975)$.

Albrow [24] pointed out that the former $S*$ now $f_0(975)$ meson has been considered to be essentially a bound state of two neutral kaons, however, a recent analysis concludes that a single narrow resonance is not enough to fit the data, the f_0 should be two close and narrow states in reality. One (988) is likely to be a bound state of neutral kaons, the other (991) couples equally to pion and kaon pairs, as expected for a glueball.

8. Arguments in favour of $K\bar{K}$ molecule structure

Calculations based on variational considerations of the $qq\bar{q}q$ state followed by a mapping onto a coupled channel meson-meson scattering problem indicate a $K\bar{K}$ molecule like structure of these resonances [25]. Weinstein [26] compares the Breit–Wigner line shape of a 600MeV wide $f_0(1300)$ with a 34 MeV wide $f_0(975)$ and a 400MeV wide $a_0(1300)$ with a 57 MeV wide $a_0(980)$. In this study the discrepancy between naive quark model considerations and the f_0 and a_0 features become clearly visible.

In addition, the elastic $I = 0\, \pi\pi$ phase shift from a coupled channel equation [27] demonstrates a good reproduction of the major experimental features.

Further, equivalent indications — as shown during the present conference by Speth — result from coupled channel calculations of $\pi - \pi$ scattering [28]. Accordingly, the sharp rise of the phase shift at about 980 MeV is due to a strong coupling of the $\pi - \pi$ to the $K - \bar{K}$ channel with an interaction *via* vector-meson exchange.

If the 988 MeV/c^2 meson could be regarded as a bound state of neutral kaons with mass: $2\times$ mass K_0 = 995.44 MeV/c^2 a well separated equivalent K^+K^- bound state with mass $\{K^+$ plus mass $K^-\}$ = 987.34 MeV/c^2 would be expected. More speculative, are there hadronic molecular charged combinations like $K^+ + \bar{K}^0$ or K^-K^0?

9. Recently available results

Additional arguments on the nature of scalar mesons at about 1 Gev/c^2 can be found in the Review of Particle Properties [29]. Due to insufficient statistics a recent study of $f_0(975)$ production from Υ decay [30] cannot distinguish between a $q\bar{q}$ or $K\bar{K}$ structure. Based on the presently available data arguments for both interpretations can be deduced from the data.

In addition, measurements at high momenta in γp, $\pi^{\pm}$p and $K^{\pm}$p reactions [31] result in cross section ratios relative to the corresponding ρ^0 production which according to the authors suggest the normal q$\bar{q}$ structure of the $f_0(975)$ meson.

Thus we are faced with the basic question of hadron spectroscopy to learn about the confinement mechanism of QCD and its prediction for the spectrum of mesons (hadrons) which is far richer than in its simple quark model and where even hadronic states without quark content are postulated as gluonic excitation of matter. A systematic study of the low energy meson-meson interaction is needed. These studies should produce $\pi\pi$, πK, $\pi\eta$, $\pi\eta'$ $\pi\rho$, $\pi\omega$, K$\bar{K}$, ηK, ηK *etc.* as isolated as possible from other hadronic states. COSY-11 is constructed for measuring precise data on these topics. A discovery of an additional state beyond those of the quark model — as known in the conventional nonets — would be an obvious candidate for a special state from those predicted by QCD as: four quark states, mesonic molecules, hybrids or even possibly glueballs.

Investigating reactions of the three body final state type pp $\to$ ppX might lead to X being one neutral meson or two mesons with zero net charge; whereas in the case of the pp $\to$ pnX reaction X is a positive charged system. Especially at the production threshold with two formed mesons involved in the final state, these then are distinguished by a very small relative momentum. This condition should allow to observe possible meson-meson interactions. Qualitatively similar arguments hold for the two baryons in the exit channel. In case of a π^+ production *via* pp reaction the final state interaction could lead to the deuteron as a simple species of dibaryons.

10. Electromagnetic interaction forming two-meson atomic states

Opposed to the hadronic meson-meson interaction experimental observation of two-meson atomic states has not been reported [32]. From antiprotonic atoms it is well known that shifts and broadening of low lying atomic energy levels and changes of their life times can be mediated by the short range strong interaction and thus giving valuable information.

Traditionally, π-π scattering has been studied indirectly *via* final state interactions in the πN $\to$ $\pi\pi$N reaction. Probably due to the intrinsic difficulty of such measurements it is observed that different experiments are not always consistent and furthermore that the extracted information are model dependent.

Recently ideas have been discussed [33, 34] to produce pionium $(\pi^+\pi^-)$ in the pd $\to{}^3$He $(\pi^+\pi^-)_{\mathrm{atom}}$ reaction. Predominantly the $\pi^+\pi^-$ atom decays to $\pi^0\pi^0$ and with much less probability to $\gamma\gamma$. Wycech and Green [35] evaluated signals relevant for a production of atomic states as pionium

($\pi^+\pi^-$), kaonium (K^+K^-) and a $K^+\pi^-$ system, distinguishing between production in S- and P-wave states.

A recoil energy distribution measurements for identifying the atomic state has been suggested [33]. A single ^{3}He spectrum should be able to distinguish between the free $\pi^+\pi^-$ pair production (threshold energy at 430.492 MeV) and the $(\pi^+\pi^-)^{1s}$ pair production (threshold energy at 430.489 MeV), since the energy of the recoiling ^{3}He nucleus changes rapidly, close to threshold in the pd $\rightarrow ^3\mathrm{He}\,\pi^+\pi^-$ reaction. For both processes all of the ^{3}He particles will recoil into a very small forward cone of $\leq \pm 0.1°$ [33].

Under very optimistic experimental conditions with a resolution of 70 keV the signal to $\pi^0\pi^0$ background ratio [36] would only be $\simeq 1\%$ due to the few eV pionium line width. As discussed above, the $K^+\pi^-$ atomic state is very difficult to be generated. Whereas the width of $\pi\pi$ and $K\pi$ atoms is supposed to be about 0.2 eV the KK width is 480 eV, making the possibility of observing K^+K^- atoms somewhat larger [36]. In addition, the basic mechanism for creating the K^+K^- atom is enhanced, since it appears *via* scalar $f_0(975)$ and $a_0(980)$ resonances.

11. The set-up of the COSY-11 experiment

Several features of the COSY ring installation serve for a measurement of the production reaction pp $\rightarrow$ ppX at threshold, with X being one or a few mesons. The high beam quality in a cooled beam mode operation together with the C-type dipole magnet allows the use of an internal target station in front of the magnet.

Resulting from compromises between the need of measuring at 0°, the need of high luminosity employing thin targets, and the need of optimizing available resources the COSY-11 collaboration proposed to use a regular COSY dipole for both separating the ejectiles from the beam and using the dipole for the determination of momenta of reaction ejectiles.

Depending on the sign of their charge the reaction products will be bent out of the COSY beam trajectory as shown in the three dimensional Fig. 3. The reaction pp $\rightarrow$ ppK^+K^- is chosen as an example, the calculations have been performed with a beam momentum 2 MeV/c above the threshold at 3.3016 GeV/c. The separation of the four ejectiles p, p, K^+, and K^- to

(i) K^- with short tracks leading into the magnet
(ii) K^+ with tracks passing through two drift chamber stacks and a scintillation detector arrangement just behind the second stack, and
(iii) the two protons with tracks again passing through the two drift chamber stacks, the scintillation detector arrangement behind them providing a start signal and (after 9 meters) a large scintillation detector providing a stop signal, in order to measure the time of flight is clearly displayed.

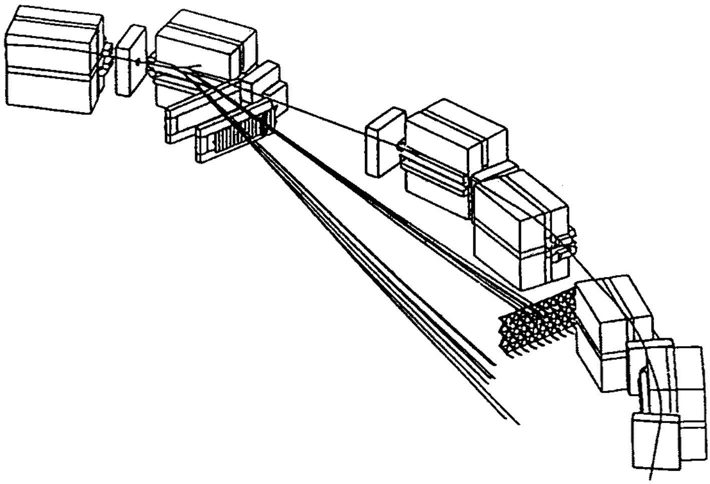

Fig. 3. A three dimensional display of the COSY-11 experimental set-up, reaction particle trajectories are shown, see the text.

Figure 3 shows only partly the essential components of the COSY-11 experiment, these are: the magnet, the vacuum chamber, the cluster target, the detector system, and the data acquisition; in addition, the beam conditions at the target station and the geometrical acceptance will have significant influences on the features of the expected data.

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