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NEW POSSIBILITIES WITH RECOILLESS KINEMATICS
USING HIGH QUALITY PROTON BEAMS

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ABSTRACT

Recoilless or "magic" kinematics which has been used successfully in hypernuclear physics has peculiar features in nucleon-nucleon interactions. It should provide a powerful tool to study low energy pion scattering, low energy pion nucleus interactions, η -nucleus interactions or the recoilless excitation of Δ or N^* resonances in nuclei.

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INTRODUCTION

Under certain kinematical conditions one can produce in an inelastic two body reaction

$$(1) \quad 1 + 2 \rightarrow 3 + 4$$

a new particle (say 4) at rest in the laboratory system. This happens at a "magic" beam momentum p_1^{mag} when particle 3 goes forward to 0° and overtakes exactly the momentum of the beam particle 1. The magic momentum p_1^{mag} depends on the masses m_i ($i=1, \dots, 4$) of the reaction partners

$$(2) \quad p_1^{\text{mag}} = \sqrt{\frac{\left[(m_1^2 + m_2^2) - (m_2 - m_4)^2 \right] - 4m_1 m_3}{4(m_2 - m_4)^2}}$$

Only the difference of the target mass m_2 and the mass of the "recoilless" particle m_4 appears in eq. 2. This means that we can embed the elementary reaction eq. (1) in the nuclear environment of a residual nucleus R without changing the "magic" condition

$$(3) \quad 1 + \begin{pmatrix} R \\ 2 \end{pmatrix} \rightarrow 3 + \begin{pmatrix} R \\ 4 \end{pmatrix}^*$$

The elementary reaction (equ. 1) which is at high energy, just creates in a direct single step process a nucleon hole by removing particle 2 from the target. The residual nucleus R is left in a simple hole configuration. Into this well defined system R now the particle 4 is introduced in a smooth, cold way with small relative energy ϵ and small momentum transfer q . In the limit of $q=0$ the orbital quantum numbers of the removed particle 2 and the introduced particle 4 will be the same and $(R+4)^*$ states will be populated which have the same orbital configuration as the target.

By changing the beam momentum or scattering angle the relative energy ϵ and momentum transfer q between particle 4 and the residual nucleus R can be tuned, and various $(R+4)^*$ particle hole configuration can be selectively populated.

In a missing mass experiment (measuring beam particle 1 and outgoing particle 3) one can reconstruct the excitation spectra of $(R+4)^*$ and study the interaction of particle 4 with the nuclear system R.

It was suggested quite some time ago to study the Λ -nucleus interaction (hypernuclei) using the elementary interaction $K^- + n \rightarrow \pi^- + \Lambda$ at its magic K^- momentum around 550 MeV/c embedded in nuclei ¹⁾. Such experiments were performed in the last decade. They have proven that magic, recoilless kinematics is really an excellent tool²⁾.

In this paper I want to draw attention to some very interesting aspects of magic kinematics in connection with nucleon-nucleon interaction. A proton beam allows to create on a nucleon recoillessly one or more pions, heavier mesons ($\eta, \rho, \omega, \dots$) or just "excitation energy". (See Table 1). Performed on bound nucleons one can introduce the new objects in a cold way into a nucleus. The low energy, low momentum transfer interaction of those objects with a well defined and cool nuclear system can be studied. To my knowledge this has never been tried so far.

Table 1: Kinematic quantities for "magic" conditions in proton-nucleon interactions. When "particle 3" is a two-nucleon system then 10 MeV/c² have been added to take into account the relative NN energy. Recoilless hyperon production is shown for comparison.

Elementary reaction				threshold momentum	"magic" quantities		
beam	target	scatt	recoilless		momentum	energy	mass
1 +	2 +	3 +	4	$p_{1\text{th}}$ MeV/c	p_1^{mag} MeV/c	T_1^m MeV	$\sqrt{s}$ MeV/c ²
p	n	d	"50 MeV"	436,8	443.3	99.5	1927
p	p	d	π^+	788.8	828.65	287.5	2027
p	p	(pp)	π^0	809.8	849.4	327.4	2034
p	n	(pp)	π^-	820.3	862.1	335.9	2039
p	p	d	$\pi^+\pi^0$	1202.7	1363.4	716.7	2206
p	p	(NN)	"300 MeV"	1308	1512	841	2258
p	n	d	η^0	1978.4	3037.9	2241.2	2782
p	p	(pp)	η^0	2014.5	3105.5	2305.8	2802
p	N	(NN)	ω	2699	8463	7576	4212
K^-	n	π^-	Λ^0	-	530.9	231.3	1.578
K^-	n	π^-	Σ^0	-	284.5	76.1	1.482

KINEMATICAL AND EXPERIMENTAL CONSIDERATIONS

The basic kinematical facts can be explained with the reaction $pp \rightarrow d\pi^+$. The elliptical polardiagrams of the π^+ momenta at various beam momenta are plotted in Fig. 1. The (low momentum) pion and (high momentum) deuteron distributions add up to the beam momentum.

$$(4) \quad \vec{p}_\pi + \vec{p}_d = \vec{p}_1 \quad (p_\pi^\perp = -p_d^\perp, \quad p_\pi^L + p_d^L = p_1^L)$$

Fig. 1 shows that, close to threshold, pions are always thrown forward by the center of mass (c.m.) movement. At high beam momenta the velocity (energy) of pions in the c.m. system becomes high enough that they can go backward in the laboratory system. The minimum (maximum) momentum pions are always at 180° (0°) in c.m. and go backward (forward) in the cm system. The magic beam momentum is reached when 180° backward pions in the c.m. system just compensate the forward boost of the c.m. system and appear at rest in the laboratory system. They are related to deuterons which are going forward with beam momentum at 0° . Deuteron angles larger than zero correspond to finite transverse deuteron momenta. These are balanced by opposite going transverse pion momenta.

Fig. 1: Polar diagrams for pion and deuteron momentum vectors in the reaction $pp \rightarrow d\pi^+$. The dependence of the maximal and minimal pion momentum on the beam momentum is indicated by the dashed curve. Backward pions have small energy for beams between 820 and 840 MeV/c.

If one allows for pion momenta up to a certain maximum (say 16.7 MeV/c which corresponds to a kinetic energy $\tau_\pi = 1$ MeV) then these are only available in a limited range of beam momenta (Fig. 2). Those low energy pions come only from a part $\Delta\Omega$ of the c.m. solid angle around 180° which is purely kinematically defined and plotted in Fig. 2. Multiplying this solid angle $\Delta\Omega$ with the momentum dependent $d\sigma/d\Omega$ (extrapolated according to ref.3) gives us a partial cross section $\Delta\sigma = \Delta\sigma(p_1)$ for low energy ($\tau_\pi < 1$ MeV) pion production (Fig. 2) which goes up to $3 \mu b$ at $p_1 \approx 820$ MeV/c. The total pp cross section here is only ~ 25 mb and dominated by elastic scattering. The low energy pions come with a rather high branching ratio⁴⁾. Kinematically they can be clearly distinguished from elastic events. The $pp \rightarrow pp\pi^0$ reaction is the third open channel. Its cross section is much smaller here.

Let us imagine that the $pp \rightarrow d\pi^+$ reaction is embedded in a nucleus. Assume that those < 1 MeV pions interact strongly with the residual nucleus R in the form of say 2 proton emission. Then this signature will appear with an energy dependent cross section like $\Delta\sigma$ in Fig. 2. It might be misinterpreted as a resonance effect in the direct channel while it would be in reality just the proof that low energy π^+R interactions are best studied at the magic kinematics.

Fig. 2: Upper part: Pion laboratory momentum p_π as a function of proton beam momentum p_p in $pp \rightarrow d\pi^+$. The solid lower curve is the minimal pion momentum (180° emission in cm). The "magic" momentum is at $p_p = 829$ MeV/c.

Lower part: Partial cross section $\Delta\sigma$ for production of pions with < 1 MeV lab energy ($\Delta\sigma = (d\sigma/d\Omega)\Delta\Omega$). The relevant $\Delta\Omega$ is shown as dashed curve.

The above kinematical considerations are not changed if we consider as scattered particle 3 not a bound deuteron but 2 independent nucleons N and N'. Their total momentum will replace p_3 $\vec{p}_3 \equiv \vec{p}_N + \vec{p}_{N'}$ and the mass m_3 has to be replaced by $\sqrt{s_{NN'}} \approx m_N + m_{N'} + \epsilon_{NN'}$. Recoilless reactions of the type

have attractive features in our context

- * They allow to get pions or other mesons of all charge states especially π^- (e.g. in $p + n \rightarrow pp + \pi^-$)
- * They allow to have the (NN') system with internal odd angular momentum thus negative parity. In contrast to $pp \rightarrow d\pi^+$ where parity conservation needs $\Delta l = 1$ the reaction $NN \rightarrow (NN') + \pi$ allows to replace particle 2 (in equ. 2) by a pion with $\Delta l = 0$.
- * In a recoilless reaction $p + N \rightarrow (pp) + X$ the two individual protons can be well separated in a magnetic spectrometer from the primary beam since they have both about half the beam momentum while deuterons at magic momentum can only be separated by time of flight from the primary beam.

There are obvious signatures related to recoilless production $p + N \rightarrow NN + X$.

- * Deuterons or (NN) combinations which go forward with a total momentum close to the beam momentum.
- * The recoilless particles X interact with the residual nucleus R. If they are in bound states with R then e.g. quasi-deuteron absorption can occur giving two nearly back to back nucleons. If X is in a resonance state a pion can be emitted in all directions with a characteristic energy.

POSSIBLE APPLICATIONS OF MAGIC KINEMATICS WITH PROTON BEAMS

A) Scattering experiments with tagged very low energetic $\pi^\pm$

The lab momentum distribution of pions in an elementary reaction $pp \rightarrow d\pi^+$ or $pp \rightarrow NN\pi$ can be tagged by measuring the scattered d or 2N system. For a secondary pion scattering on another target (or in the same hydrogen target) then the pion direction and momentum is known. In comparison with experiments on normal pion beams one has the advantage that very short distances between pion production and pion scattering are feasible so that pion decays in flight are negligible even at very low momenta. The decay length of a 1 MeV $\pi^\pm$ (16.7 MeV/c) for example is 94 cm. This leads to negligible decays in flight in a double scattering setup with typically 10 cm size but it is prohibitive for a say 10 m long standard pion beam where only a fraction of $2.4 \cdot 10^{-5}$ of the pions would survive.

B) Study of hadronic pion nucleus systems

The pion is at the same time mediator of NN interaction and partner in πN interactions. Implanting a real low energy pion in a nucleus could therefore lead to a complex but also interesting situation. Of course pions are absorbed in a nucleus but the absorption width Γ is much smaller than the pion mass. About $\Gamma \approx 10$ MeV can be estimated from π -R potentials⁵⁾. If pion-nucleus resonant or bound states exist or not can be checked in a missing mass experiment

$$(6) \quad p + \begin{pmatrix} R \\ N \end{pmatrix} \rightarrow (\text{or } d \text{ NN}) + \begin{pmatrix} R \\ \pi \end{pmatrix}^*$$

where the mass spectrum of the $(R+\pi)^*$ system is determined from the forward $p \rightarrow d$ or $p \rightarrow (NN)$ kinematics. One optimizes the production of $(R\pi)^*$ systems by working at the magic momentum. If there is a $(R+\pi)^*$ resonant system than also monochromatic pions should be observable in all directions from the $(R+\pi)^*$ system at rest with a yield which is dependent on the beam momentum like $\Delta\sigma$ in fig. 2. The maximum pion yield should occur at a beam momentum which is "magic" for the production of the pion mass and the excitation energy of the $(R+\pi)^*$ system. There might be experimental indications of this situation⁶⁾ in experiments where one sees a "flash" of low energy pions at 90° in inclusive $p+\text{Cu}$ interactions around 350 MeV. One should extend these experiments and check if deuterons or 2N systems go forward with beam momentum in coincidence with the pion flash.

C) Study of deeplying π^- atomic states

Pionic atoms are a well known example of bound pion nucleus systems. They are normally studied by stopping π^- in a target and observing the X-ray cascade of π^- captured in the Coulomb field of target nuclei (from outside in). The deeplying atomic states in heavy nuclei where hadronic distortions are strongest are not accessible this way since just the hadronic absorption of π^- becomes so much faster than the radiative transitions that the X-ray cascade dies out. The recoilless production of the type

$$(7) \quad p + \begin{pmatrix} R \\ n \end{pmatrix} \rightarrow pp + \begin{pmatrix} R \\ \pi^- \end{pmatrix}^*$$

should be very favourable in populating deeplying atomic states from inside out⁷⁾. The position and width just of the hadronically distorted deeplying states could be determined in a missing mass experiment with the trigger signatures described above. One can get information about pion nucleus low energy interaction in the central high density region of a nucleus.

D) η mesons in nuclei

One can repeat the arguments for recoilless production of η mesons. The total $pp \rightarrow d\eta$ cross section in the magic region around 3050 MeV/c is about 100 to 200 μb ⁸⁾. η energies below 1 MeV can be obtained for proton beam momenta between 2810 MeV/c $< p_1 <$ 3360 MeV/c in a part of the solid angle $\Delta\Omega/\Omega \leq 7.6 \cdot 10^{-4}$. The η production is symmetric in the c.m. system and should be enhanced in 0° and 180° direction which would enhance the production in the recoilless region.

The η is an isoscalar. In contrast to the isovector pion and it should probe different aspects of meson nucleus interactions. With its higher mass of 550 MeV/c it could allow to use its absorption inside nuclei in some respect like central low energy $\bar{p}$ annihilation.

E) Recoilless excitation of nuclei

In (p,d) or (p, 2N) reactions one can also transfer pure excitation energy without recoil into nuclei.

For deeplying hole states (instead of a 140 MeV pion one considers a $\approx$ 50 MeV hole) the magic momentum would be around 450 MeV/c (see Table 1). At this momentum, selected hole states should stand out very clearly since the remaining nucleus is disturbed minimally⁹⁾.

Finally one could introduce without stress on the nuclear structure energies which allow to excite in a resonant way Δ or N^* resonances inside nuclei ($\approx$ 300 or $\approx$ 500 MeV respectively). If there are modifications of width and mass of these resonances by the nuclear medium, they should be measurable. A signature for those resonances might be the rather isotropic emission of energetic pions.

CONCLUSION

Recoilless kinematics in proton experiments seems to open up exciting new possibilities. It may be that the predicted effects have not been seen so far because nobody has searched for them. With the good beam quality in the relevant energy range which should be available at the cooler ring of IUCF and then also in Uppsala and Jülich one could try out some of the ideas described here.

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