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ABSTRACT

The theoretical understanding of the nucleon-nucleon interactions at energies below 350 MeV is briefly reviewed. A simplifying method for the determination of the NN amplitudes experimentally, independent of energy, is outlined. Experimental effort in Berkeley in achieving this goal is illustrated.

Theoretical understanding of the two-nucleon interaction has made much progress in recent years. At incident kinetic energies below 350 MeV, there is a unique set of phase shifts established by Arndt and MacGregor[1] in both the pp and np systems. These authors have performed both an energy-dependent and an energy-independent analysis with about 700 data points from 25 to 310 MeV and have fitted these points with 27 phase shifts and mixing parameters. Phase shifts as high as H-wave have been used in their search (in the case of energy-dependent search, as many as 66 parameters have been used), and one-pion-exchange contributions have been included for higher partial waves. A rough theoretical understanding has been proposed by Arndt, Bryan, and MacGregor,[2] using the contributions of the exchange of four bosons (π, σ, ω, and ρ-meson) in the Born approximation, and a correction from the strip approximation to the Mandelstam representation to achieve unitarity. By using the four coupling constants and a mass (M_σ) as free parameters in a fit, these authors were able to reproduce pp phase shifts below 350 MeV. (Unfortunately, the σ-meson has not been experimentally established yet!)

At energies between 350 and 700 MeV (the intermediate energies), at which inelastic processes become important, not only are more phase shifts of higher ℓ required to fit the data, but the phase shifts also become complex; all of a sudden one is confronted with approximately 60 phase shifts and mixing parameters (approximately half of them for the pp case, I = 1, system alone). The situation certainly becomes difficult to cope with! However, by using cleverness, simplifying assumptions, and the limited amount of data around 650 MeV (with large errors) measured in Dubna,[3] the Japanese[4] and Russian[3] groups have been able to extract sets of phase shifts smoothly joining to the lower energy set. However, as the data points become more precise and numerous, a more detailed and extensive analysis such as that of the lower energies must be performed, and it is not clear that the phase-shift analysis can be extended indefinitely to higher energies; and it is possible that its meaningfulness will become less and less apparent, due to the complexity of the parametrization.

A different parametrization scheme has been proposed by Wolfenstein,[5] to serve as a meeting ground between experimental data and theoretical models. On the basis of fundamental assumptions of charge and rotation symmetries, and parity and time-reversal conservations, Wolfenstein was able to decompose the scattering matrix into five complex amplitudes. Here, I shall present it in a slightly different form:

$$M^I(T,\theta) = \left[(e+f) + ic\,(\sigma_{1n} + \sigma_{2n}) + (e-f)\,\sigma_{1n}\sigma_{2n} + (g+h)\,\sigma_{1\ell}\sigma_{2\ell} + (g-h)\,\sigma_{1m}\sigma_{2m}\right]^I (T,\theta) \tag{1}$$

where I = isospin of the two-nucleon system,

T= lab system kinetic energy of the beam nucleon,

θ = c.m. scattering angle,

$\sigma_{is} = \underset{\sim}{\sigma}_i \cdot \hat{s}$

$\underset{\sim}{\sigma}_i$ = the Pauli spinor for nucleon 1 or 2, either before or after scattering,

$\hat{s}$ = a unit vector in the direction $\hat{\ell}$, $\hat{m}$, or $\hat{n}$,

$\hat{\ell} = (\underset{\sim}{k}_i + \underset{\sim}{k}_f)/|\underset{\sim}{k}_i + \underset{\sim}{k}_f|$

$\hat{m} = (\underset{\sim}{k}_f - \underset{\sim}{k}_i)/|\underset{\sim}{k}_f - \underset{\sim}{k}_i|$

$\hat{n} = \hat{\ell} \times \hat{m} = (\underset{\sim}{k}_i \times \underset{\sim}{k}_f)/|\underset{\sim}{k}_i \times \underset{\sim}{k}_f|$ is the normal of the scattering plane,

$\underset{\sim}{k}_i$ and $\underset{\sim}{k}_f$ = the c.m. momentum of particle 1 (beam particle) before and after the scattering process, respectively, and

c, e, f, g, h (complex functions of T and θ, labelled by I) = the Wolfenstein amplitudes or Wolfenstein parameters, sometimes called form factors.[6]

Because of the extended Pauli exclusion principle, the amplitudes exhibit the following properties under the reflection about θ = 90 deg:

$$\begin{array}{ll} c^1(\theta) = c^0(\pi-\theta), & c^0(\theta) = -c^0(\pi-\theta) \\ e^0(\theta) = -e^1(\pi-\theta) & e^0(\theta) = e^0(\pi-\theta) \\ f^1(\theta) = -g^1(\pi-\theta) & f^0(\theta) = g^0(\pi-\theta) \\ h^1(\theta) = h^1(\pi-\theta) & h^0(\theta) = -h^0(\pi-\theta)\,. \end{array} \tag{2}$$

I shall skip a few steps and state that the experimental measurables are of the form

$$\{A, B; C, D\} = 1/4\, \mathrm{tr}\, \{M\sigma_{1A}\sigma_{2B}M^{\dagger}\sigma_{1C}\sigma_{2D}\},$$

where A, B, C, and D take on the directions 0, ℓ, m, and n;

A(B) are the directions of polarization of particle 1(2) being thus prepared before scattering. Here 0 means unpolarized, and $\sigma_{i0} = 1$;

C(D) are the direction of polarization of particles' 1(2) being measured after the scattering, and 0 means polarization not measured.

For example, the differential cross section has the following dependence:

$$I_0 = \{0, 0; 0,0\} = 2[|c|^2 + |e|^2 + |f|^2 + |g|^2 + |h|^2] , \qquad (3)$$

and the polarization

$$I_0 P = \{0, 0; 0, n\} = \cdots = \{n, 0; 0, 0\} = -4 \,\mathrm{Im}[ce^*] . \qquad (4)$$

There are altogether 256 such expressions to write and, fortunately, only a small fraction of the 256 are nonzero and linearly independent.[7]

Now let us consider the experimental determination of the amplitudes. For a given isospin state, I = 0, or 1, or a given particle state pp, nn, or np, one needs to perform experiments to measure at least nine different observables at each energy and angle to determine the five complex amplitudes. (There are nine real numbers, one phase being arbitrary.) The set of nine experiments, in order of increasing experimental complexity, can be chosen, for example, to be $I_0, P, D, D_t, R, R_t, C_{nn}, C_{\ell m}$, and R' (the subscript t stands for transfer). One can see that the last seven measurements are triple-scattering experiments (double scattering if a polarized target is used), and R' even requires a precession of the spin of the outgoing nucleon by the magnetic field.

On the other hand, the same experiments are being performed in both the pp and np systems at the same energy, T, and angle, θ, plus one more angle, $\pi-\theta$, in the np system. (Call this "one set.") Due to the interference term in the I = 0 and I = 1 system, one can write three independent equations equating observables to amplitudes.[8]

For example, from Eqs. (2) and (4), we obtain

$$I_0 P^1(\theta) = I_0 P^{pp}(\theta) = 4\,\mathrm{Im}[\,c^1(\theta) e^{1*}(\theta)] \tag{5a}$$

$$I_0 P^0(\theta) = 2[\,I_0 P^{np}(\theta) - I_0 P^{np}(\pi - \theta)\,] - I_0 P^{pp}(\theta) = -4\,\mathrm{Im}[\,c^0(\theta) e^{0*}(\theta)] \tag{5b}$$

$$I_0 P^{\mathrm{interf}}(\theta) = 2[\,I_0 P^{np}(\theta) + I_0 P^{np}(\theta)] = -2\,\mathrm{Im}[\,c^1(\theta) e^{0*}(\theta) + c^0(\theta) e^{1*}(\theta)]\,. \tag{5c}$$

In this case there are 10 complex amplitudes (19 real numbers) to be determined at each angle and energy. In principle, 6 such "sets" of experiments, plus one extra pp or np experiment, should suffice to determine them. In practice, due to the bilinear dependence of the observables on the amplitudes, and noninfinitestimal size of experimental uncertainties, in order to determine the Wolfenstein amplitudes uniquely, more than the minimum "sets" of experiments are required.

With the present advancement of experimental techniques, one can design experiments in such a direction as to measure the same pp and np parameters with essentially the same experimental setup. I shall illustrate this point on the experiments performed in Berkeley.

The experimental data in the energy region between 350 to 700 MeV is not quite as complete as in the region below 350 MeV. Since the polarization and differential cross-section data are numerous (except for I_0^{np}), most of them are listed in Wilson's book,[9] and the newer ones are summarized by Rose,[10] I shall mention only the data in triple-scattering experiments.

At about 400 MeV, there is a concentration of data in the pp system: D, R, A, A', and C_{nn}, $C_{m\ell}$ from Chicago,[11] with C_{nn} and

$C_{m\ell}$ also from Liverpool.[12] About 600 MeV, there are many measurements from Dubna:[3] C_{nn}^{pp}, $C_{m\ell}^{pp}$, R^{pp}, A^{pp}, R^{pn}, and D^{pn}. There are also measurements of C_{nn}^{pp} by polarized target, at 575 MeV at Orsay and Saclay[13] and 680 MeV at Berkeley.[14]

To illustrate the point of simultaneous measurement of pp and np parameters, we have measured pp and pn polarization parameters[15] at energies of 310, 400, 500, 600, and 700 MeV on virtually the same setup (shown in Fig. 1). I want to point out that the shape of the polarization parameter has relatively weak dependence on energy. A polynomial fit in both the energy and angle summarizes the data (Fig. 2). From the available differential cross-section data, by means of Eq. (5) plus similar expressions for the differential cross section, one can obtain the isospin = 0 parameters. The differential cross section and polarization parameters (I = 0) at 350, 500, and 630 MeV are shown in Fig. 3.

Another experiment scheduled for the 184-in. cyclotron in the summer of 1967 is to measure I_0, D, R, and R' parameters for both the pp and np systems in the energy region 500 to 700 MeV. The proposed scheme is shown in Fig. 4. Here the beam polarization is achieved by scattering at angles between 12 and 30 deg on an H_2 or D_2 target. The scattered (polarized) proton or neutron beam then rescatters on an H_2 or D_2 target, and the polarization of the second scattered protons (neutrons) is analyzed by the third scattering in a wire chamber interlaced with carbon (polyethylene - carbon). The monitoring and triggering schemes are outlined in Fig. 4. We hope to achieve measurements with an error of 10% or less.

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FIGURE LEGENDS

Fig. 1. Experimental setup for the measurement of P^{NN} at energies between 300 and 700 MeV in Berkeley.

Fig. 2. Angular dependence of $P^{NN}(\theta)$ between 300 and 700 MeV from Berkeley results.

Fig. 3. Angular dependence of $I_0^{I=0}$ and $P^{I=0}$ of NN (I = 0) state.

Fig. 4. Proposed setup for the Berkeley $I_0{}^{NN}$, D^{NN}, R^{NN}, and R'^{NN} experiments.

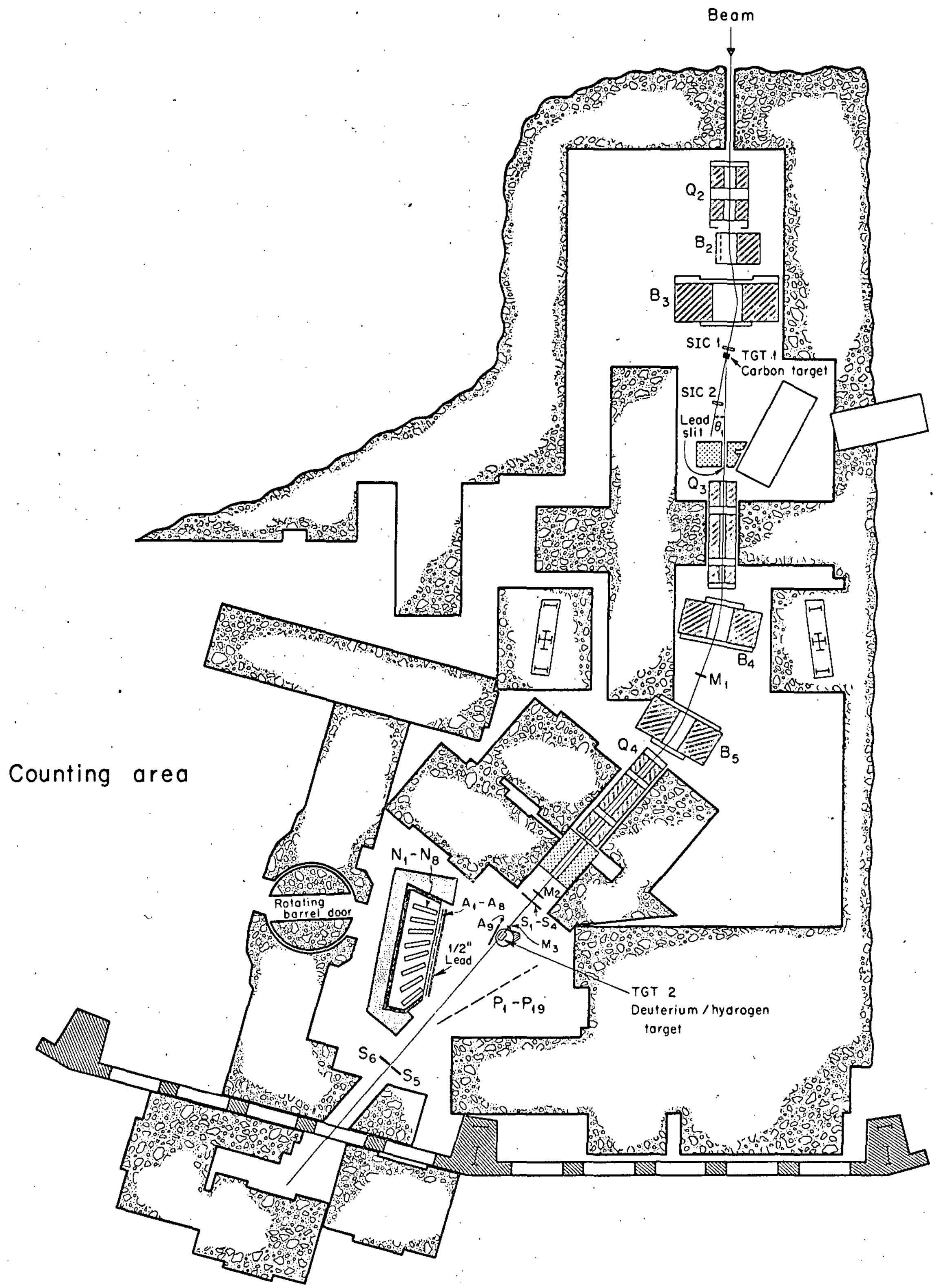
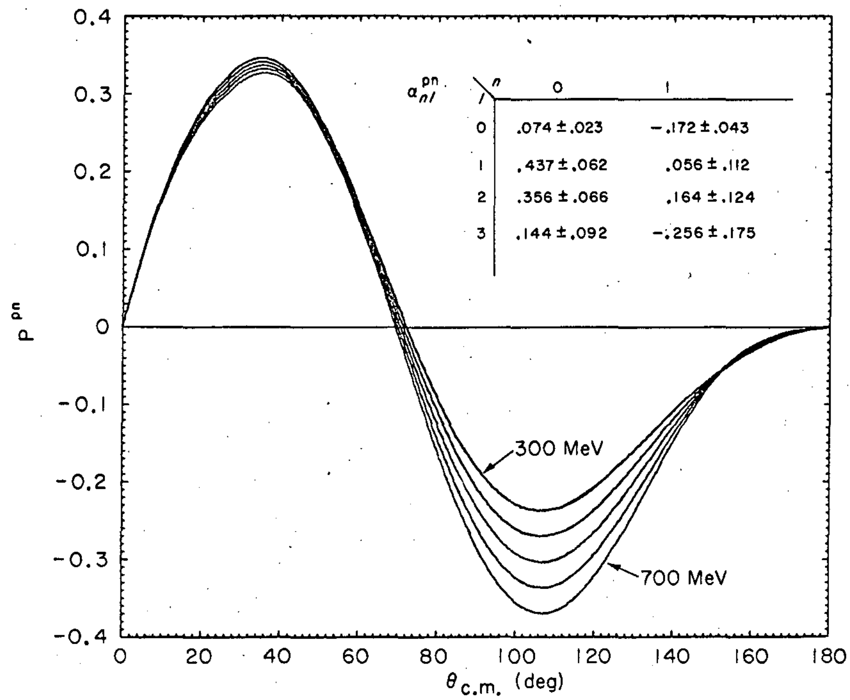


Fig. 1

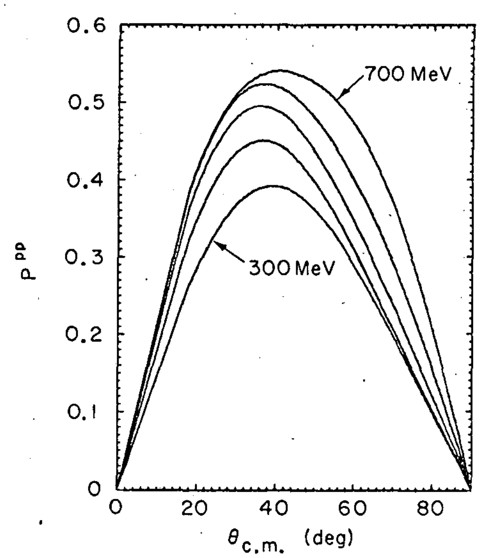
MU-35241

$P^{NN}(\theta,T) = \sin\theta \; \Sigma_{nl} \; a_{nl}^{NN} \; T^{n} \; P_l(\cos)$, T in BeV



a_{nl}^{pn}

l \ n	0	1
0	.074 ± .023	−.172 ± .043
1	.437 ± .062	.056 ± .112
2	.356 ± .066	.164 ± .124
3	.144 ± .092	−.256 ± .175



a_{nl}^{pp}

l \ n	0	1	2
1	.295 ± .283	1.971 ± 1.104	1.033 ± 1.040
3	−.543 ± .438	3.283 ± 1.733	−3.347 ± 1.649
5	−.002 ± .328	−.196 ± 1.359	.534 ± 1.342

Fig. 2 XBL 672-890

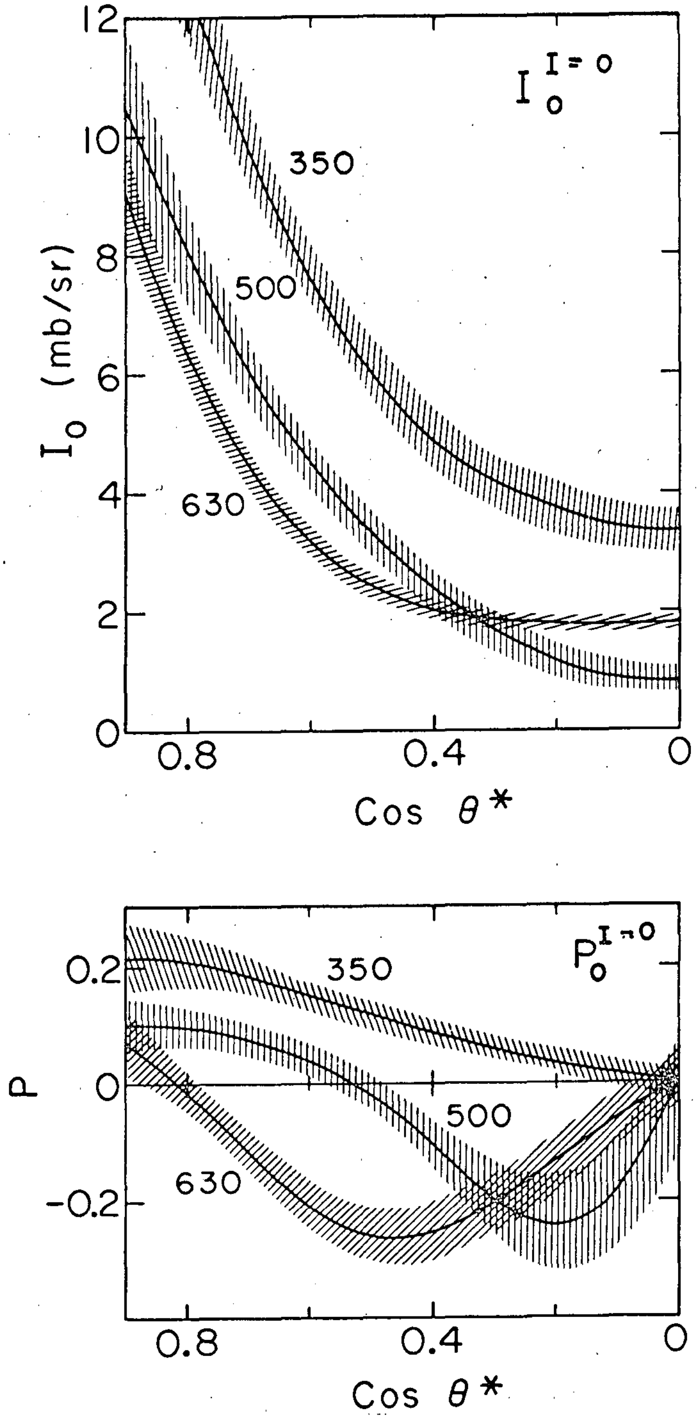
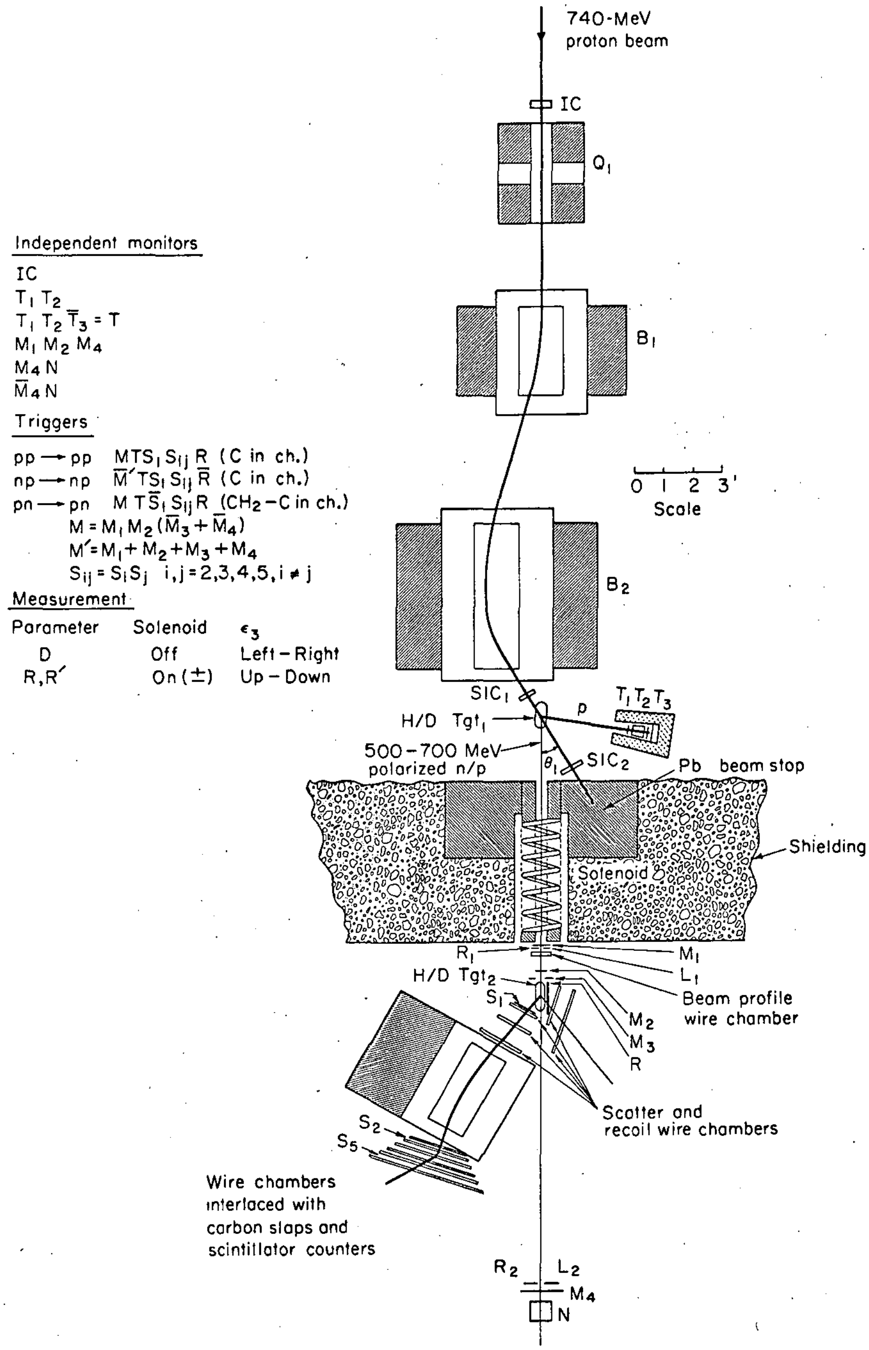


Fig. 3 XBL671-402



XBL672-891

Fig. 4